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OSCILLATORY INJECTION OF GASEOUS FUEL INTO A DUCTED AIR STREAM

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ABSTRACT: Oscillation of fuel composition in ducted air flows with oscillatory injection of gaseous fuel was studied using temperature difference as scalar in flows involving radial injection of an oscillatory fuel jet and radial and axial injection of a steady air-fuel jet with oscillatory fuel composition into a ducted air stream. Local measurements of mean and oscillatory velocity and scalar in turbulent flow were carried out with flow rates, frequency and amplitude of imposed oscillations as variables. The decay of the oscillation of the scalar was faster than that of mean velocity and mean scalar, and attenuation was strongest in the shear layer. Flow past a bend attenuated oscillations by around 40 % and past a bluff-body downstream of a jet resulted in faster decay of oscillations than in flows without a bluff-body. The influences of frequency in the range between 100 and 220 Hz and mass flow ratio of cross flow to jet between 5 and 15 on attenuation of oscillations was small.

1. Introduction

Periodic variation in the composition of an air-fuel mixture, although not always desirable in combustion equipment, has useful applications as, for example, in active control of combustion-driven oscillations in premixed flames [1-4]. Oscillation of the fuel composition so that the oscillatory heat release is out of phase with the combustion-driven oscillations results in their attenuation and may be achieved by oscillatory injection of part of the fuel into the combustor duct or into a secondary air stream entering the combustor duct upstream of the flame-holder [3,4]. Effective control depends on the amplitude and coherence of the oscillatory heat input and the present study is concerned with the attenuation of oscillation of fuel in flows of relevance to active control. The oscillation of fuel composition is quantified in flows comprising an oscillatory jet of gaseous fuel injected radially into a tube carrying secondary air and radial and axial injection of a nearly steady secondary air-fuel mixture with oscillating fuel composition into the main duct carrying air. The effects of a bend in the secondary air tube and a bluff-body located downstream of the secondary air-fuel jet are also quantified. Fuel concentration was replaced by temperature difference as scalar in the measurements which include the mean velocity and scalar and their fluctuation at the imposed frequency. The absolute temperature difference between the fluid streams was around 10 % so that the effect of variation in density was negligible.

2. The Experimental Set-up and Measurement Techniques

The flow sections of the geometries of Fig. 1 were of nonconducting material. The jet of cold air (hereafter referred to as fuel) emerged from a 2 mm orifice in the fuel receiver of geometry 1a and was oscillated by a needle-valve mounted on a 300 W vibrator whose displacement varied directly with input voltage from a power amplifier and inversely with the square of the frequency. The frequency of oscillation of fuel was limited to around 200 Hz since higher frequencies implied small amplitudes of oscillation of the fuel jet. In geometries 1b and 1c, the 2 mm fuel jet entered radially into a tube of diameter 7.4 mm with a straight upstream length exceeding 100 diameters to ensure fully developed flow of secondary air with mean temperature up to 45 degC higher than that of the fuel. The tube legth downstream of the fuel jet was straight in geometry 1b and had a bend of radius 25 mm in geometry 2c. In geometry 1d the secondary air-fuel jet entered the main duct of diameter 80 mm coaxially and in geometry 1e radially at the wall. Measurements were also made in geometries 1d and 1e with a 40 mm flame-holding disk downstream of the inlet of the secondary air-fuel mixture. The mean flow rates of the fuel, secondary and main air of up to 0.015, 0.18 and 2.7 kg/min, respectively, measured by calibrated float-type flow meters, were associated with mass flow ratios of jet to cross-flow between 5 and 15 and Reynolds numbers up to 25 000 in the secondary air tube and 40 000 in the main duct, corresponding to turbulent flow conditions comparable with those in the active control measurements of refs [3,4].

Hot-wire anemometry was used to quantify mean and rms velocities in geometries 1a and 1b. Spectrum analysis of the amplified hot-wire signal yielded the amplitude of the fluctuating component of velocity at the imposed frequency. The rms of the fluctuating component at the imposed frequency was less than 2 % of the mean velocity compared with turbulence intensity of order 4 % at the exits of geometries 1b and 1c due to the
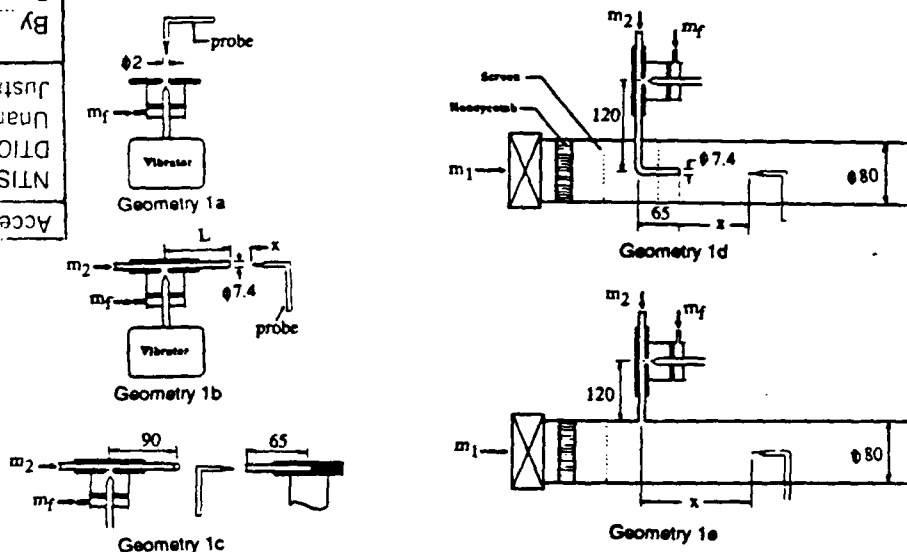
Fig. 1: Flow Arrangements

small ratio of fuel to secondary air and damping, and mean velocities were measured using Pitot tubes in geometries 1b to 1e. Temperature was measured using a calibrated cold-wire resistance thermometer. The rms temperature at the imposed frequency was obtained by spectrum analysis of the temperature signal in preference to using probability density distributions obtained by ensemble averaging because of the shorter sampling period and better precision in the presence of large amplitudes of incoherent fluctuations. The amplitude was determined by subtracting the spectral power at the imposed frequency from that in the absence of imposed oscillations and was subject to experimental uncertainty within 5% in flow arrangements 1b and 1c and around 10 % in 1d and 1e associated with smaller amplitudes and incoherent oscillations. The amplitude of oscillations across a flow section is quantified by the normalised spatial average of the rms,

$$\bar{\theta}^* = \int \rho U \bar{\theta} \, dA / m_f$$

where U is the mean axial velocity, ρ is the density, $\bar{\theta}$ is the rms of the oscillation in temperature, t, normalised by the temperature difference, ΔT, between the secondary air and fuel and m_f is the mass flow rate of fuel.

Repeatabilty was within the limits of experimental uncertainty and further details of the measurement techniques and experimental precision are available in ref. [5]

3. Results

Velocity measurements at the exit of the orifice of geometry 1a confirmed that the amplitude of fluctuation of the jet velocity was directly proportional to the vibrator input voltage and inversely proportional to the square of the frequency. The fluctuating velocity signal at 120 Hz was sinusoidal for a travel of the needle valve of up to 0.48 mm, estimated on the basis of the characteristics of the vibrator, at which the velocity fluctuated between zero and twice the mean value. The results of Figs 2 to 6 are for geometries 1b to 1d and a mean fuel flow rate of 0.015 kg/min oscillated at 120 Hz with an amplitude of 0.015 kg/min, and secondary and main air flow rates of 0.15 and 1.35 kg/min, respectively, with secondary air temperature 30 degC higher than that of the fuel and main air at 15 °C. Some measurements were carried out, especially at small amplitudes of oscillation, with a temperature difference of 45 degC.

Figure 2 shows typical distributions of mean velocity and mean and rms of the passive scalar at the imposed frequency in the exit plane of geometry 1b along two orthogonal diameters for two values of downstream tube length. The asymmetry of the exit velocity and oscillatory scalar profiles in the vertical plane for the shorter tube are due to the radial jet in cross flow and the more developed flow in the longer duct shows greater symmetry. The amplitude of the oscillations decreases sharply in the vicinity of the wall due to the larger radial gradient in phase caused by the boundary layer. The overall attenuation of the oscillation is, however, small as may be seen from Table 1 since the phase difference between the mean flow at the point of

injection and the exit of the longer tube is less than half a cycle. The amplitude of the oscillation at 220 Hz was about 5% less. The difference in amplitude is, however, small and of the same order of magnitude as the experimental uncertainty. The exit velocity profile for geometry 1c in Fig. 3 shows the effect of the bend associated with a centripetal acceleration of the order of 10^5 m/s^2 and the attenuation of the oscillation by around 40 % was mainly due to the the large gradients in velocity and phase caused by the reversed flow region along the inner side of the bend. The influence of the amplitude of oscillatory input and mass flow ratio of secondary air to fuel on attenuation was also small for the range of flow conditions examined.

The use of flow smoothing screens upstream of the secondary-air fuel jet resulted in a nearly uniform mean velocity distribution in the main air flow in the exit plane of the secondary air-fuel jet in geometry 1d. Figure 4 shows radial profiles at three stations and axial profiles of the mean velocity and mean and rms scalar. The rates of decay of the mean jet velocity and scalar are in accord with those for turbulent jets and the imposed oscillations in the jet were too small to influence the spreading of the jet. The slight asymmetries in the profiles in the horizontal plane are due to that in the jet issuing from a tube with an upstream bend. The decay of the rms scalar is faster than that of the mean properties due to the gradient in phase, in addition to the diffusion effects which cause a decay of mean properties, and increases with distance from the axis of the jet. Although the normalised rms of the fluctuation at x = 2.4 D is only 30 % less than that at the exit plane of the jet, the peak amplitude is about an eighth of that at the jet exit (see Table 1). The rms scalar for a larger main air flow rate of 2.7 kg/min was around 5 % less than that with the mass flow rate of 1.35 kg/min due to increased dilution of the oscillating flow. The difference is, however, less than the experimental uncertainty of around 10 %.

Figure 5 shows radial profiles for the mean velocity and the mean and rms scalar at x = 1.5 D for geometry 1e, and the normalised average of the rms scalar is less than a third of that at the jet exit (see Table 1). The oscillations were insignificant at x = 2.4 D. Radial injection leads to faster diffusion of the imposed oscillations than with axial injection due to the agitation of the main flow by the radial jet. The attenuation was also an order of magnitude greater than in geometry 1b due to the mean velocity in the 80 mm duct being a tenth of that in geometry 1b so that radial gradients in phase develop over shorter axial distances.

The location of a disk of diameter 40 mm (0.5 D) at a distance of 0.1 D from exit of the secondary air-fuel jet of geometry 1d resulted in severe damping of the oscillations due to impingement and oscillations could not be detected 0.9 D from the jet. Although Table 1 shows that the spatial average of the oscillations in the plane of the disk located 0.9 D downstream of the jet was only 5 % less than that without the disk, the maximum amplitude of oscillation in the plane of the disk was only a third of that at the same axial location in the absence of the disk owing to the spread of the jet in the presence of the bluff-body. Fig. 6 shows that the oscillations decay rapidly with distance downstream of the disk owing to the effect of the turbulent wake behind the disk on the transport of the oscillatory scalar and oscillations could not be detected beyond 1.2 D from the disk. The influence of the disk was, however, smaller in geometry 1e since the amplitude of oscillations were largest close to the duct wall opposite the point of entry of the jet and away from the disk.

4 Discussion
The mean scalar distribution measured 20 tube diameters downstream of the oscillatory jet (geometry 1b) indicates good mixing and the normalised spatial average rms value of around 0.3 is close to the expected maximum of 0.35 corresponding to a sinusoidal oscillatory input. The attenuation was small due to the shortness of the tube. The damping of the oscillations near the wall of the secondary air-fuel tube and in the shear layer of the jet in parallel flow was due to the gradient in phase caused by the radial variation in mean velocity so that a higher frequency would be associated with a larger gradient. Although differences of around 5 % in attenuation between 120 and 220 Hz are consistent with the above, measurements with a wider range of frequency values and longer tube lengths are necessary to be more conclusive. Slow fluid flow also leads to an increase in gradient in phase and impingement and regions of recirculatory flow are associated with large gradients in phase and severe attenuation of oscillations.

Active control depends on the oscillation of heat release out of phase with the instability and a large local amplitude of oscillation of the fuel concentration near the flame front could be more advantageous than a more even distribution of the oscillation of fuel, which will also be subject to greater incoherence in phase. As slow fluid flow, impingement, flow reversal and agitation of the flow are associated with the decay of the oscillations, parallel injection of the oscillatory air-fuel jet or the fuel close to the burning zone is likely to conserve the amplitude and coherence of the oscillatory input and enhance control.

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Geometry	Station		$\tilde{\theta}_{max}$	$\tilde{\theta}^*$
	x,mm	x/D		
1b, L=65mm	1		0.044	0.307
L=145mm	1		0.037	0.295
1c	1		0.020	0.176
1d	70	0.9	0.008	0.145
	190	2.4	0.003	0.12
	270	3.4	0.001	-
1d with disk	70	0.9	0.003	0.14
1e	120	1.5	0.004	0.1
1e with disk	120	1.5	0.004	0.1

Table 1: Spatial average of rms scalar

Fig. 4: Profiles of mean velocity and mean and rms scalar, geometry 1d, (a) x=70mm, (b) x=190 mm, (c) x=270mm, (d) axial profile; $\bar{U}$=4.3m/s.
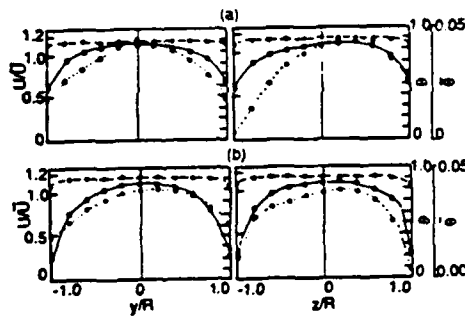

Fig. 2: Profiles of mean velocity and mean and rms scalar, geometry 1b, (a) L=65mm, (b) L=145mm; x=1mm, $\bar{U}$=bulk mean velocity=55m/s.
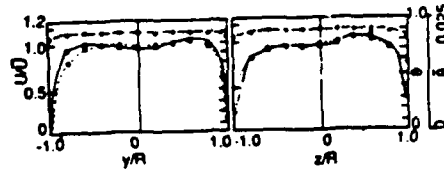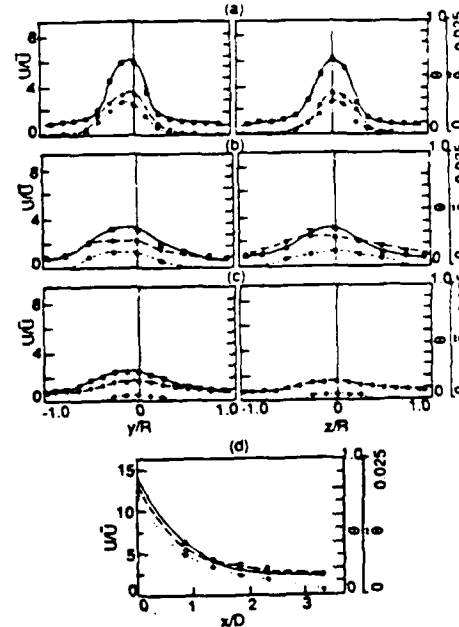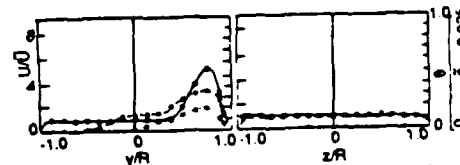
—□— $U/\bar{U}$, -O— – θ, ●····· $\tilde{\theta}$

Fig. 5: Profiles of mean velocity and mean and rms scalar, geometry 1e, x=120 mm. $\bar{U}$=4.3m/s.

Fig. 3: Profiles of mean velocity and mean and rms scalar, geometry 1c, x=1. $\bar{U}$=55m/s.

Fig. 6: Longitudinal profiles of mean velocity and mean and rms scalar, geometry 1d with 40 mm disk 70 mm downstream of jet, y=30mm, z=0.